SMART ECOLOGY
Surfing the Wave of Wildlife Tracking Data

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Pour l’enfant, amoureux de cartes et d’estampes,
L’univers est égal à son vaste appétit.
Ah! que le monde est grand à la clarté des lampes!
Aux yeux du souvenir que le monde est petit!

C.B. (1821-1867), *Le Voyage*

Abstract

Technological developments of the last years have provided scientists and wildlife managers with new tools to monitor animal movements. Massive and detailed positioning data can be generated by global navigation satellite systems (e.g. Global Positioning System, GPS) with minimal work by operators, allowing reduced sampling intervals, and increased accuracy and performance compared to previous technology. Furthermore, data can be remotely transferred to operators, making real-time monitoring of animals possible. As a consequence, the interaction between science and technology has been rapidly evolving the discipline of ecology: knowing where animals move, when and in which kind of habitat, can help to build a mechanistic understanding of key concepts of behavioural and evolutionary ecology, including resource use, home range and dispersal, response to climate change, and population dynamics, among others. However, the availability of large data sets can challenge scientists by their complexity that requires innovative and efficient data handling and analytical tools. In fact, to extract the information from raw GPS tracking data (and other wildlife-attached monitoring devices) required to address complex environmental questions at local as well as global spatial scales, many steps are required. These include data storage, processing, analysis and sharing, but GPS tracking routinely generates larger data sets than software tools commonly used by biologists in the past could handle. Instead, good scientific practice requires that data are securely, efficiently managed to minimize errors, increase the reliability and reproducibility of inferences, and ensure data persistence (e.g. consistent use of data on multiple occasions and by several persons). For GPS-based locations flexibility in managing very large data sets from different devices, the ability to manage spatial time series generated in real-time, and the possibility to integrate tools for data analysis and visualization in a single software environment are key characteristics to fully exploit the potential of these tracking technologies. Data sharing and their long term preservation for studies beyond their initial scope is another important element for all scientific data. This is especially crucial when considering that collecting wildlife tracking data is often expensive and may impose risks on animal welfare.

In my research, I address these questions. I start with a critical evaluation of the requirements for good management and processing of GPS wildlife tracking data. Then I identify and develop a suite of tools and methodological approaches that satisfy these requirements. I explore current research in wildlife data management and finally suggest a possible direction for development, based on a modular software architecture with a spatial database at its core. I propose methodological approaches and tools to optimize data handling and particularly the integration of GPS data with other sensors data and with environmental information derived from remote sensing. This innovative approach offers the opportunity to model location data as objects characterizing the presence of individuals in space and time within

their habitat. My work focuses on GPS-based location data, but is also valid for other kinds of wildlife monitoring data acquired with remote, automatic device-based techniques.

The ultimate goal of my PhD research is to build a better information system to support research in the movement ecology domain making the potential offered by GPS wildlife tracking data more efficient. Good data management is needed to produce better science. Proving this statement empirically is difficult, although the best evidence is the enhanced efficiency and consistency in results. This is especially relevant currently because new and more sensors, more large-scale animal tracking studies, more international collaborative projects, and more pressing issues on the state and the future of our environment are forcing researchers to tackle data management as one of their primary efforts. This is confirmed by the growing demand for data management systems as a tool for research. I think that the intrinsic consistency and integrity of spatial databases represents a necessary scientific infrastructure for rigorous science *per se*, preventing error propagation, optimizing performance of analysis and improving robustness of inferences. In particular, this favours the move from simple descriptive approaches towards mechanistic models with higher explanatory and predictive power, focusing wildlife research on biological, rather than statistical, significance.

Sintesi

Lo sviluppo tecnologico degli ultimi anni ha fornito ai biologi che studiano la fauna selvatica e agli amministratori che la gestiscono, nuovi strumenti per monitorare il movimento e il comportamento degli animali. I sistemi globali di navigazione satellitare (ad esempio Global Positioning System, GPS) possono generare una enorme mole di dati con grande precisione e con un lavoro minimo da parte degli operatori, permettendo intervalli di campionamento ridotti e prestazioni molto migliori rispetto alle tecnologie precedenti. Inoltre, i dati possono essere trasferiti in remoto agli operatori, rendendo quindi possibile il monitoraggio in tempo reale degli animali.

L'interazione tra il rapido sviluppo tecnologico e la scienza sta plasmando i contorni stessi dell'ecologia: sapere dove gli animali si muovono, quando e in che tipo di *habitat* può aiutare una comprensione meccanicistica dei concetti chiave dell'ecologia comportamentale ed evolutiva, compresi, tra gli altri, l'uso delle risorse, la risposta al cambiamento climatico, e la dinamica demografica. Tuttavia, la disponibilità di grandi quantità di dati molto complessi può mettere in difficoltà gli scienziati e richiede una gestione dei dati innovativa ed efficiente e specifici strumenti analitici. Estrarre dai dati grezzi di localizzazione le informazioni che servono per rispondere alle questioni ambientali che vengono poste agli scienziati a scala sia locale sia globale, è un processo complesso che include l'acquisizione, l'archiviazione, l'elaborazione, l'analisi e la condivisione dei dati. La quantità di dati generati, però, è molto più grande di quella che gli strumenti software comunemente utilizzati dai biologi nel recente passato sono in grado di gestire. Invece, una buona prassi scientifica richiede che i dati siano archiviati e gestiti in modo sicuro ed efficace per ridurre gli errori, aumentare l'affidabilità e la riproducibilità dei risultati, e garantire la persistenza dei dati sul lungo periodo. Per realizzare tutto questo è necessario sviluppare sistemi informativi flessibili e capaci di gestire serie di dati spazio-temporali generate in tempo reale, di integrare gli strumenti di analisi e visualizzazione in un unico ambiente software, e di permettere la condivisione dei dati e la loro conservazione a lungo termine.

Nella mia ricerca, ho cercato di dare una risposta a queste necessità, partendo da una valutazione critica dei requisiti per una buona gestione ed analisi dei dati di monitoraggio della fauna, per finire con l'individuazione e lo sviluppo di un insieme di strumenti e approcci metodologici che soddisfano questi requisiti. Ho delineato una possibile direzione di sviluppo basata su un'architettura software modulare con un database spaziale al suo centro. Ho sviluppato strumenti per ottimizzare la gestione dei dati e in particolare l'integrazione dei dati GPS con altri dati da sensori remoti e con informazioni ambientali telerilevate. Questo approccio offre l'opportunità di modellare i dati di localizzazione come oggetti che caratterizzano la presenza nello spazio e nel tempo degli animali nel loro *habitat*. Il mio lavoro si

concentra sui dati di localizzazione GPS, ma è valido anche per altri tipi di dati di monitoraggio acquisiti con sensori di monitoraggio remoti.

L'obiettivo finale della mia ricerca di dottorato è costruire un sistema informativo che realizza le potenzialità offerte alla disciplina scientifica dell'ecologia del movimento dal monitoraggio basato sulla tecnologia GPS, e su altri sistemi di monitoraggio remoto. Una buona gestione dei dati è un elemento necessario per produrre scienza migliore. Dimostrare empiricamente questa affermazione è difficile, anche se la prova migliore è la maggiore efficienza del processo scientifico e la coerenza e qualità dei risultati. Creare strumenti appropriati per la gestione dei dati sta diventando particolarmente rilevante in questi anni dove il numero sempre maggiore di sensori, i programmi ambiziosi di monitoraggio ambientale a scala regionale e globale, la diffusione di un approccio condiviso alla raccolta ed analisi dei dati, e la rilevanza e urgenza dei problemi relativi allo stato e al futuro del nostro ambiente, stanno costringendo i ricercatori ad affrontare la gestione dei dati come uno dei punti principali su cui concentrare i loro sforzi. Ciò è testimoniato dalla crescente domanda di sistemi di gestione dei dati come strumento per la ricerca. Io credo che la coerenza intrinseca e l'integrità dei database spaziali rappresenta un'infrastruttura scientifica necessaria per una scienza rigorosa, impedendo la propagazione degli errori, ottimizzando le le analisi e migliorando la robustezza dei risultati. In particolare, questo può favorire il passaggio da semplici approcci descrittivi verso modelli meccanicistici con maggiore potere esplicativo e predittivo.

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Chapter 1

Introduction

1.1 A Smart New World

In the last ten years we have seen an astonishing wave of technological innovations that are directly impacting our lives. Every day new tools emerge that offer a plethora of opportunities to improve the quality of our cities and explore our environment in more informed and conscious ways. The domains where this process is occurring are commonly described with the adjective “smart”. The label “smart” is still quite a fuzzy concept and is used in ways that are not always consistent. Cook and Das (2004) define “smart environment” as “a world where different kinds of smart device are continuously working to make inhabitants’ lives more comfortable”. In general, a smart environment is composed of a set of devices (e.g. sensors), of services (e.g. wireless network and applications that transform data into useful information), and people that exploit the information to achieve their goals in the best possible way (e.g. information-driven decision making). “Smart” is the innovative and efficient use of technological advances to improve our knowledge of the world and the sustainable use of its resources.

This research is an example of a study that tries to apply these concepts to a specific domain: movement ecology. In science the technological innovations often have determined conceptual advances to the point to generate new scientific disciplines (for example, see what had come out from the invention of the telescope or the microscope, among other revolutionary instruments). In this perspective, the synergy between movement ecology and Global Positioning System (GPS)-based radiotelemetry for animal tracking (the monitoring and recording of animals’ sequential positions), the subject of this research, is an exciting example: rapid advances in positioning, sensor and data transfer technologies are being applied to the study of animal behaviour and ecology. Today, ecologists sitting at their desks can check the movements of many of the most difficult to study species. The interaction between science and tracking technology is rapidly evolving and shaping the discipline of ecology: knowing where animals move, when and in which kind of habitat, can help a mechanistic understanding of key concepts of behavioural and evolutionary ecology, including resource use, home range and dispersal, response to climate change, and population dynamics, among others (Cagnacci et al., 2010).

In the last 15 years, GPS technology and other new remote data-logging systems have gradually revolutionized the data that can be collected from animals’ movement and the information that can be derived from them. GPS telemetry can provide large, continuous, high-frequency data of animal movements that can be complemented by other information on behaviour, internal state of the animals and the habitat offering the opportunity to perform quantitative and mechanistic ecological analyses (Cagnacci et al., 2010). On the other side, GPS data can challenge scientists with their complexity that requires innovative and efficient data handling and analytical tools. For animal-borne telemetry data, flexibility in managing very large data sets from different devices, the ability to manage spatial time series generated in real-time, and the possibility to integrate tools for data analysis and visualization in a single software environment are key characteristics to fully exploit the potential of these tracking technologies. The sharing of data and their long term preservation for uses beyond their initial scope is another important element for all scientific data and even more for wildlife tracking where data collection has potential consequences to the welfare of animals and is often expensive (and usually supported by public money).

In conclusion, the efficient and effective management and analysis of wildlife tracking data generated in this evolving "smart" framework is a hot topic in ecology. It is key not only for conservation purposes but also to better understand the impacts of climate change and environmental factors on specific species. It can support decision making and policy formulation and is used, among the many other possible applications, to investigate and control the spread of human diseases for which wildlife is a vector.

1.2 ⅓ Science, ⅓ Technology, ⅓ Technique and 1 Orange Slice, for Garnish

Movement is a fundamental characteristic of life, and particularly of animals. It plays a major role in determining the fate of individuals, populations, and ecosystems, including the evolution and diversity of life (Nathan, 2008). The understanding of the causes, patterns, mechanisms, and consequences of organismal movement is the subject of a specific branch of ecology usually referred to as movement ecology. Nathan et al. (2008) tried to establish a solid theoretical basis for this emerging discipline. These authors describe a conceptual framework depicting the interplay among four basic mechanistic components of organismal movement: the internal state (why move?), motion (how to move?), navigation capacities of the individual (when and where to move?) and the external factors affecting movement. The clear definition of what they call "movement ecology paradigm" demonstrates the maturity and importance of this science and its relevance.

Movement ecology is the reference scientific framework of animal tracking. Tracking data management can be seen as the product of the interactions among a scientific domain (movement ecology), a technological component (the biologging sensors that measure the position of animals in space and time) and a technical element (here referring to the set of methodological approaches, algorithms and software tools necessary to deal with movement data). An illustration of the relationships of these three components is reported in the Venn diagram (Figure 1.1). Specifically, the application of remote sensors to animals is defined as biologging (see Section 2.1), where movement is one of the most commonly measured properties of animals. The tools used to deal with animal movement data fall under the broader field of mobility data management. Biometry is the application of mathematics and statistics to biological sciences, and particularly to ecology. Spatial databases are among the most effective and consolidated tools when it comes to analysis and management of movement ecology data. In fact, this research can be seen as an effort to integrate three disciplines: biologging, biometry, and mobility data management. In the first place this is due to my interests and competences, that I always (and particularly during my PhD) tried to develop horizontally to get a better overview of technical problems in a broader dimension. The other reason resides in the history of this research. I started to work on these topics in 2005 with a collaboration

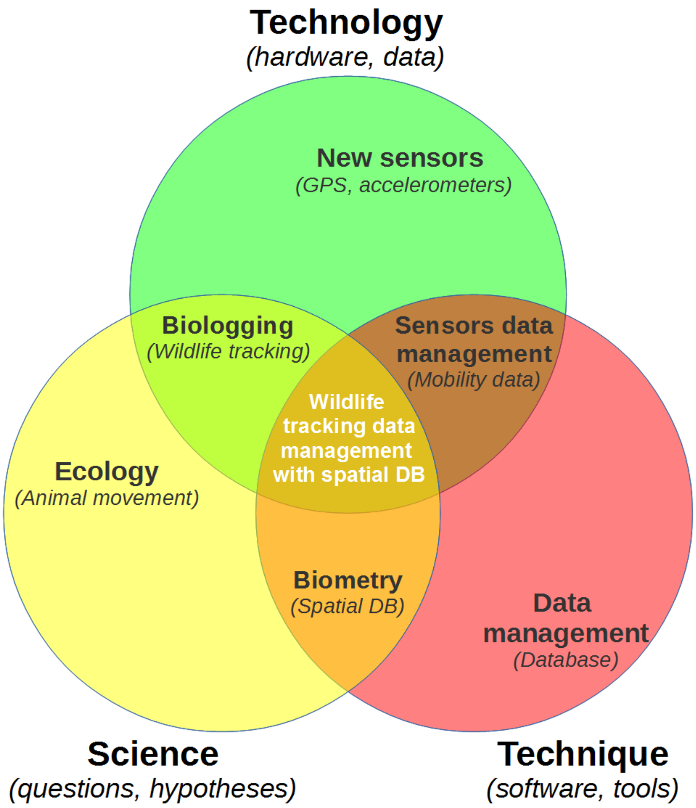

Figure 1.1: Wildlife tracking data management as intersection of different disciplines

with the Alpine Ecology Centre (Trento, Italy), now Edmund Mach Foundation, where I worked with Francesca Cagnacci, a young biologist managing a large project on roe deer (*Capreolus capreolus*) tracking. The results were very promising and the professional collaboration has been continuing and consolidated until now. The reseach itself has been involving other scientific institutes (e.g. Bruno Kessler Foundation, Trento, Italy; Norwegian Institute for Nature Research, Trondheim, Norway; Max Plank Institute, Radolfzell, Germany; Leibniz-Institute for Zoo and Wildlife Research, Berlin, Germany), universities (e.g. Swedish University of Agriculture Sciences, Umea, Sweden; University C. Bernard, Lyon, France) and private companies (e.g. Vectronic Aerospace GmbH). My PhD at IUAV can be considered as part of this path. Most of the achievements of this research result from the open and collaborative attitude between two experts, one with knowledge of the technical issues (database, GIS, remote sensing, data and environmental modelling) and the other with a deep background in biology and a clear understanding of the main scientific questions to address in animal ecology. In fact, the technical implementation of an information platform always has implications and impacts on the theoretical approach of scientific problems that determined its design, thus affecting the formulation of requirements, in a process with many recursive steps. This iterative and interactive process is only possible when the language spoken by experts of different disciplines (in this case, biology and data management technology) is common and when the experts involved want to listen first, in order to have a common understanding of problems and solutions. To achieve this, flexibility, curiosity and an open-minded attitude are elements as important as the technical expertise for the identification of innovative solutions. I believe that from this point of view, this collaboration is a success story that I am particularly proud of and the results, particularly with the EURODEER project (see Section 3.3), are witness of this.

1.3 What this Research is About

Technological developments of the last years provided scientist and wildlife managers with new tools to monitor animal movement and behaviour. Particularly, global navigation satellite systems (GNSS) are constellations of orbiting satellites working in conjunction with a network of ground stations that provide geo-spatial positioning of a user's receiver with global coverage (Tomkiewicz et al., 2010). At the moment, the most used GNSS is the GPS network. This technology represents a powerful tool for wildlife studies (Hebblewhite and Haydon, 2010). GPS tracking systems can record huge amounts of highly accurate animal locations with minimal work by operators, thus allowing reduced sampling intervals, and increased accuracy and performance when compared with very high frequency (VHF) radio tracking systems. Furthermore, data can be remotely transferred to operators (e.g. using the Global System for Mobile Communications (GSM) network, or communication satellite systems as Argos or Iridium), making real-time monitoring of animals possible. GPS tracking data sets can be used to address animal ecology questions (e.g. resource selection, animal movement, foraging behaviour, predation) from a completely new perspective (i.e. closer to the animal's point of view). However, the availability of large data sets also poses a number of challenges, for example the need for appropriate analytical techniques to deal with spatially and temporally autocorrelated data, or the development of modelling approaches to exploit the information embedded in continuous time series of animal locations. In fact, to extract the information from raw GPS tracking data (and other wildlife-attached monitoring devices) required to address complex environmental questions at local as well as global spatial scales, many steps are required. These include data storage, processing, analysis and sharing. GPS tracking routinely generates larger data sets than software tools commonly used by biologists in the recent past could handle (Rutz and Hays, 2009). When I began my research the existing dedicated software tools for wildlife studies were mainly developed for VHF radio-tracking data, which are characterized by small and discontinuous data sets, and focused on data analysis rather than data management. Spatial data, such as animal locations and home ranges, were traditionally stored locally in flat files, accessible to a single user at a time, and analysed by a number of independent applications without any common standards for interoperability. This approach usually requires data replication and export/import procedures that are time-consuming and present potential sources of error. Moreover, data preprocessing has to be repeated for every scientific question to be addressed, resulting in task replication and inefficiency. Instead, good scientific practice requires that data are securely, efficiently managed to minimize errors, increase the reliability and reproducibility of inferences, and ensure data persistence (e.g. consistent use of data on multiple occasions and by several persons).

In my research I address these questions, beginning with a critical evaluation of the requirements for good management and processing of GPS wildlife tracking data to conclude with the creation of a suite of tools and methodological approaches that satisfy these requirements. Together with a number of other colleagues, I explored current research in wildlife data management and suggested a possible direction of development, based on a modular software architecture with a spatial database at its core. Specific concerns, including interoperability, data modelling and integration with remote sensing data sources are part of this work, with a special attention to satellite-based image time series (e.g. normalized difference vegetation index, NDVI). My work focuses on GPS-based location data, but is also valid for other kinds of wildlife monitoring data acquired with remote, automatic device-based techniques. Examples include data sets produced by accelerometers that are frequently associated with GPS sensors, depth sensors (often combined with other animal-borne loggers), video-monitoring or wireless sensor network monitoring. All these techniques can potentially produce near real-time, high frequency, large data sets that share with GPS-based location data the same advantages and challenges of data storage and management.

In conclusion, the ultimate goal of my PhD research, is to build a better information system to support research in the movement ecology domain making the use of GPS wildlife tracking data more efficient. In order to take full advantage of GPS animal tracking data, while preventing error propagation and optimizing analysis performance, data handling systems must be robust to store large amount of complex data sets and to preserve them permanently. Simultaneously, they have to be flexible to accommodate data from new sensors and new protocols of data collection. This is especially relevant currently because new and more sensors, more tracking studies at regional and global scales, more international collaborations, and more pressing issues on the state and the future of our environment are forcing researchers to tackle data management as one of their primary efforts. This is confirmed by the growing demand for data management systems as a tool for research and by the number of scientists and wildlife managers that read the articles that my colleagues and I published in the last years on this subject.

Finally, as I carried out my PhD research with no direct fundings from IUAV or other institutions, I explored all possible synergies between my research and my professional collaborations as free lance consultant. On the one side this sometimes constrained the time I was able to dedicate to my PhD project, on the other side I benefitted from inputs coming from many different projects and fields of application, broadening the horizon of my research.

1.4 Content and Structure of the Thesis

During the time spent on this research, I had the opportunity to publish the results of my work in a number of papers and book chapters. In fact, the possibility to dedicate time to develop the outputs of my professional collaborations into scientific publications to be submitted and shared with the scientific community, was one of the main reasons for which I decided to become a PhD student. All published documents went through a rigorous peer-review process. Because the methodological aspects and results of my research are described in detail in these documents, I herein only report an extended summary in agreement with the "New technologies and information for the environment" PhD Committee. I illustrate the golden thread that connects all activities of my research and the main results, giving references to the publications for a complete description of the topics discussed. Chapter 1 introduces the broad subject of my research in the general framework of the PhD School. Chapter 2 presents a description of wildlife tracking, including the scientific background and the potentialities and limitations of this technology. Chapter 3 builds the core of the thesis. It shortly discusses the findings of my research and reports all abstracts of my publications. In particular, it describes the use of a spatial database system to manage wildlife tracking data. It illustrates the tools that can be integrated in an information system to properly model, process and analyse tracking data and the related ancillary information. The same chapter reports the case study of EURODEER (http://www.eurodeer.org), an open project which mission is to support a collaborative process of data sharing on roe deer among 24 research institutes and universities across Europe. Here I had the chance to apply most of the concepts developed during my research and it was the basis to produce additional scientific outputs. Finally, Chapter 4 synthesizes the main achievements of my research and illustrates possible future developments in this field. In Annex 1, I list all published products of my research with full bibliographic references.

Chapter 2

An Insight into Wildlife Tracking

Monitoring wildlife is often a challenging task particularly for those species that are elusive or that live in environments where direct observation is difficult or impossible. Over the past five decades, miniaturized animal-borne tags have been developed that enable scientists to remotely measure the physical characteristics of the environment and the reactions of free-ranging, undisturbed animals to it. These technological advances contributed to the creation of a new branch of ecology usually called "biotelemetry", "biologging" or "animal attached remote sensing" (Cooke et al., 2004; Ropert-Coudert and Wilson, 2005). These terms have little etymological differences but are commonly used interchangeably. A definition of this science might be the "investigation of phenomena in or around free-ranging organisms that are beyond the boundary of our visibility or experience" (Boyd et al., 2004). Telemetry devices that have been successfully used by biologists for basic ecological questions as well as applied research in conservation and environmental monitoring, cover a wide range of taxa (invertebrates, fish, amphibians, reptiles, birds, marine mammals, non marine mammals) and biological variables (blood flow rates, activity, light, temperature, salinity, pressure, vibration). A review of early applications can be found in Cooke et al. (2004) and Ropert-Coudert and Wilson (2005).

Animal tracking is the most basic and widely used type of biotelemetry. It involves determining where an animal is located spatially (sometimes referred to as locational, fix or positional telemetry). Biologging applications have permitted new discoveries on the lives of many species substantially advancing both basic and applied research (Rutz and Hays, 2009). The most relevant application of biologging technologies is related to the quantitative movement analysis (Nathan, 2008). Knowing where an animal is in space and time, can provide important information on its behaviour, ecology and social interactions. With the support of additional sensors, for example accelerometers and remote sensing environmental data from satellite platforms, scientists are able to link animal movements to their habitat, as well as inter- and intraspecific interactions, how they pursue prey, alter their behaviour in the presence of conspecifics or manage their energy budgets (Rutz and Hays, 2009). Interestingly, marine biology, where boundaries to human senses are apparent and no other approach yielded the required information, was the first field of animal ecology to use telemetry (Boyd et al., 2004).

The technological advances in the miniaturization of electronics, reduced energy consumption, extension of battery life and reduced costs make GPS telemetry feasible for an increasing array of species and number of individuals that can be tracked, generating an exponential growth in the quantity of movement data collected (Wall and Wittemyer, 2014). Moreover, multi-sensor devices are becoming available that can measure multiple behavioural variables at a time, extending the information available to scientist, but also increasing data complexity in terms of management and analysis (Cagnacci et al., 2010).

2.1 A Historical Perspective

Observation of animal movements in their environment is as old as human history (Focardi and Cagnacci, 2013). In the past, the most common method was the direct observation at a distance, which was later supported by the use of binoculars or telescopes. Terrestrial animal movements have also been monitored via ground-tracking in snow or soil. In more recent times, field biologists experienced the limitations of direct observations that can provide only a small glimpse into an animal lifetime track and is biased by our senses, animal reactions to human presence, and animal habits that make most of them secretive and unseen. Therefore biologists understood that it was necessary to change the perspective from the observer to the observed, leading to the advancement of technological innovations (Cagnacci et al., 2010).

Remote animal tracking began in the early 1960s with the advent of VHF tracking (Kenward, 2001), starting a new era in the study of animal ecology. Since then, biotelemetry devices have evolved generating an exponential increase in the numbers of studies and publications. With VHF technology, animals are equipped with transmitters emitting a radio signal that can be received by VHF radio receivers. Receivers must be somewhat close to the animals to triangulate their positions which implies a time and labour-intensive data acquisition process in the field with the potential to affect animal behaviour (Millspaugh and Marzluff, 2001). The resulting precision of recorded positions is generally low.

Satellite tracking followed in the 1970s when satellite transmitters began to use the Argos satellite tracking system based on ultra high frequency (UHF) tags. This technology clearly emerged in the 1980s as an alternative method of mapping long-distance movements of migrating animals, but the accuracy of the positions (several hundred meters to kilometres) was still low for many ecological applications (Millspaugh and Marzluff, 2001). The most revolutionary advancement in obtaining precise spatio-temporal information on animal positions in the last 20 years, especially when coupled with data transmission technologies, has been the use of GPS. It was developed in the 1970s for military purposes and became available for civilian use in the 1990s. Telemetry using GPS has several advantages, particularly the ability to determine a position automatically and continuously with high precision (Tomkiewicz et al., 2010; Cagnacci et al., 2010). The use of GPS for wildlife tracking became very popular among biologists in the early 2000s, with the removal of "selective availability" (i.e. the accuracy of the satellites was no longer intentionally degraded for non US military applications). GPS-positions are stored on board and can be retrieved once the sensor is recuperated, but several systems to access the positioning data while the tag is still attached to the animal have evolved (Tomkiewicz et al., 2010). Positioning data can be remotely accessed using either a satellite link, a VHF-, UHF- or GSM-link. An interesting and complete review of papers related to wildlife tracking with GPS that have been published since 2000 is reported in Zimmermann (2013). Her analysis shows how the use of this technology reached a maturity stage with a progressive shift of focus in publications from methodological to ecological issues. Another detailed report on successful applications of GPS technology to wildlife in Australia is reported by Matthews et al. (2013). With the most recent developments, the potential of biotelemetry devices is being extended to include a larger range of variables that can often be monitored with multi-sensors devices.

2.2 The GPS (r)Evolution

The GPS, also known as NAVSTAR, began in 1973 when the United States Department of Defense developed a satellite-based three-dimensional positioning system with 24-hour worldwide coverage. The system consists of three components: 1) the satellites emitting signals continuously (called space segment and composed of 24 satellites orbiting about 20,000 km above Earth), 2) the ground control stations that monitor and manage the satellites, and 3) the ground receivers (called GPS receivers, GPS units, or simply GPS) that use the information received in the satellite signals to estimate their position on the globe by measuring the time for the signal to travel from the satellite to the GPS receiver. Measuring the time from each of (at least) four satellites (of known positions) allows three-dimensional position fixing (Tomkiewicz et al., 2010). Since the selective availability was decommissioned, the typical horizontal position error is less than 30 meters. Early receivers required up to 30 minutes to find GPS satellites and determine their first position. The newest receivers are equipped with improved systems for fast satellite acquisition resulting in a time to first fix of 30 seconds or less.

The size, weight and duration of the battery are crucial elements for wildlife tracking, because it determines which species can carry a GPS device and for how long the same individual can be monitored. It is commonly recommended that the weight of a tag should not exceed 3% of the animal's body mass for birds (Millspaugh and Marzluff, 2001), and 5% for mammals. Battery consumption is one of the main limiting factors and receiver power management is critical in finding a threshold between device weight and operational life. Another technical aspect of wildlife tracking that requires special care are the extreme environmental conditions in which many species live and instruments are therefore exposed to (e.g. extreme temperatures) as well as external forces resulting from animal movements (e.g. physical interactions between animals). This implies that applying GPS devices to animals requires many innovations also in the robust design of devices.

Proper data transfer technologies transmitting data from the device to the user are required to make GPS an effective wildlife monitoring tool. This part of the data acquisition process developed independently of the GPS system. Many data retrieval systems are available (Tomkiewicz et al., 2010):

- Store onboard systems. GPS data are acquired and stored in the unit and then downloaded from the memory when the unit is recovered. In this case, real-time monitoring is not possible.
- Data recovery using a VHF beacon data transmitter. A special version of the conventional VHF beacon is used to encode GPS-based location data on the VHF beacon data transmission.
- Data recovery using radio modem technology.
- Data recovery using Argos systems.
- Data recovery using GSM. Many GPS systems deployed on animals use GSM telephone data services, but while these are widely available in Europe and Asia, there are many vast areas throughout the world (e.g. much of North America, Australia and sparsely populated Africa) without GSM services.
- Data recovery using LEO, Iridium or Globalstar satellite systems.
- Mobile ad hoc networks. It is possible to configure each of the deployed GPS devices as a separate node in a mobile network that can communicate with each other. When an animal is in proximity

with another one, it acquires its data. At the end, if animals have frequent contacts, the remote retrieval of data from all marked animals depends only on querying one device.

Prices of GPS devices for wildlife tracking have been dropping as a consequence of the increasing number of researchers who began using this technology that is also benefitting from components developed for other larger sectors of business. Also the size of the devices has decreased, giving the opportunity to monitor new species (Cagnacci et al., 2010). This favorable trend is generating an ever increasing amount of data highlighting the need for proper data handling and analysis techniques (Boyd et al., 2004).

2.3 Analysis of GPS Data: an Evolving Framework

Modelling and analyzing components of animal movement is inherent to many questions in animal ecology. In fact, ecology is fundamentally spatial, with ecological processes occurring on heterogeneous landscapes: movement is the glue that ties ecological processes together (Cagnacci et al., 2010). The quantity and frequency of GPS data offer many opportunities to improve habitat modelling and management and our understanding of basic ecology of many species (Hebblewhite and Haydon, 2010). At the same time they present considerable challenges not only from a data management perspective, but also to traditional analytical approaches that were mainly developed for VHF telemetry. Data analyses methods that suit the characteristics and possibilities of GPS data are undergoing an intense development and are hot topics for biologists. Some of these new statistical challenges include the quantification of GPS bias (Frair et al., 2010), the statistical modelling of highly (spatial and temporal) correlated data (Fieberg et al., 2010) and the appropriate movement modelling approaches (Smouse et al., 2010).

One striking example of the interesting interplay between ecological theory and the evolution of analytical approaches that are driven by GPS data is the advancement of the home range concept. A home range can be defined as the area where an animal lives and travels during its normal activities of food gathering, mating and caring for young. For example, among the new methods of data analysis for space use, home ranges and utilization distributions make use of data-intensive techniques such as kriging and non-linear generalized regression models for habitat use. Mechanistic home-range models, derived from models of animal movement behaviour, promise to offer new insights on the relationship between home ranges patterns and the response of animals to their environment (Kie et al., 2010). Moreover, the general definition of home range does not specify how to spatially define its extent and does not take into account different intensities of use (i.e. time spent) in different area. Traditional home range estimation methods, usually based on VHF data, include minimum convex polygons (MCPs), and normal distribution kernel density. While MCPs are known to commonly overestimate the home range size, the latter, more sophisticated approach has a number of limitations when applied to GPS data. First of all, kernel smoothing ignores the temporal sequence of locations that are considered independent although the spatio-temporal auto-correlation is one of the most valuable pieces of information provided by the frequent GPS sampling. In fact, much can be learned by studying the causes and consequences of correlation in tracking data sets. In the past, ecologists considered correlation as a problem because it violates the assumption of independence in traditional statistical inference traditionally used with non-automated data collection (Fieberg et al., 2010). To remove the autocorrelation, some authors propose to subsample data, reducing the value of the resulting estimate and ignoring part of the available information. Kernel home ranges estimation methods do not take into account possible variation in the data acquisition frequency potentially resulting in higher importance to areas where sampling was more intense instead of an area more intensively used.

High sampling rates available through GPS monitoring systems make it possible to accurately estimate home ranges, including over relatively short time periods such as months, and new analytical approaches are trying to explore this opportunity. Brownian bridges are an example to estimate the probability of an animal being at a specific location in between fixes, thus modelling the movements in space and time. A Brownian bridge is a continuous time stochastic process with an expected value of the bridge of zero at points in time where animal locations are obtained. Conversely, the height of the bridge is minimal and its breadth maximal midway between two sequential location estimates and, hence, uncertainty about the actual location of an animal is maximal at midway locations (Kie et al., 2010).

Another important approach to the study of animal movement that takes advantage of the information that can be derived from GPS data is the animal movement trajectory, with a large suite of methods already available to movement ecologists (Calenge et al., 2009).

Studying how and why an animal uses a defined space requires mechanistic approaches able to model a home range on the basis of the underlying patterns of movement behaviour over a specified period of time that results from the spatial distribution of critical or limiting resources (Smouse et al., 2010). GPS data can give a relevant contribution to the definition of mechanistic models of animal space use allow to predict how space use will change in response to changing landscapes or animal populations.

In my work (see Section 3.2) I explored approaches that can be used to integrate analysis into the management steps, thereby exploiting the functionalities of spatial databases. This is done in three ways: 1) developing simplified algorithms that can be implemented into a database and applied to very large data sets in addition to traditional data mining methods; 2) preprocessing data to allow complex algorithms to be run with increased efficiency in a statistical environment; 3) connecting database and statistical software to facilitate the coupling of the opportunities offered by the two tools.

2.4 Limitations of GPS Tracking

GPS-based telemetry is an important advancement in movement ecology, but it is not the best suitable technology for all purposes and several of its limitations are discussed in literature. For an extended review of possibilities and limits of GPS see Hebblewhite and Haydon (2010). The main drawback of wildlife GPS tracking are listed below.

- Harsh environmental conditions and low load-carrying abilities by smaller animals limit the number of species that can be telemetered.
- GPS devices, as any other measurement tool, are affected by errors. The two main types of error are 1) spatial inaccuracy and 2) missing data due to failed location attempts, especially in environments with dense canopy cover or unfavourable topography (e.g. bottom of narrow valleys). Their combined effect can lead to biased inferences on animal spatial behaviour (Frair et al., 2010).
- The technology is still heavily limited by battery life and by archival memory limits (Tomkiewicz et al., 2010).

- Ethical considerations can constrain the application of telemetry devices where these may negatively affect animals, and potentially even reduce their survival, compared to non-invasive observation method (Boyd et al., 2004).
- Although several advanced analytical techniques able to deal with high frequency GPS data are reported in the bibliography (see for example Cagnacci et al. (2010)), they are often not yet fully refined, or still require exceptional computational power and highly specialized skills.
- Tomkiewicz et al. (2010) highlight that device vendors have usually little time to test new devices due to the fast technological developments, which can lead to high failures, especially in harsh environments. For example, Kaczensky et al. (2010) report that 70% of a total of 29 Argos-based sensors and 69 GPS-based sensors were affected by various problems.
- GPS collar costs are an order of magnitude higher, but quickly decreasing, than the average costs for VHF collars (although GPS collars greatly reduce the human costs associated with VHF data collection).
- The use of GPS tends to prevent biologists from conducting and experiencing fieldwork, limiting their capabilities to correctly interpret biotelemetry data.
- More data does not necessarily imply greater knowledge in understanding animal ecology and conservation (Hebblewhite and Haydon, 2010). Researchers must often opt for fewer GPS units over a greater number of VHF units which may result in a weaker study design, reduced sample sizes and poorer statistical inference at the population level.
- Having animal positions with very high temporal resolutions (e.g. every 5 minutes) may give the potentially false impression that fine spatial and temporal scale dynamics are relevant while sometimes processes are operating at larger spatio-temporal scales (Hebblewhite and Haydon, 2010).
- The environmental data to which animal movements can be linked (e.g. satellite-based environmental information) for analysis (e.g. habitat selection studies) are often not available at the same fine spatio-temporal resolution as GPS data, reducing the benefit of the higher spatio-temporal accuracy of GPS locations.
- There is a danger that ecologists may lose sight of the ultimate goal of hypothesis testing for the sake of gathering ever larger amounts of data. To counter this trend, there has been a tendency to concentrate on animal movements, reducing the pressure to develop technologies that will measure other forms of state (Boyd et al., 2004).

Many of these remarks are quite general and can be applied to any technology. In fact, as any tool, also GPS technology should be used only when appropriate and with a specific study objective. The progression of GPS-based wildlife research shares characteristics with many other innovative technologies in science: the method was established first, while the questions were asked later (Zimmermann, 2013). The problem is the possible misuse of this tool, not the technology itself, and for this reason ecologists have established clear recommendations and guidelines (see for example Latham et al. (2015)). In fact, one of the key concepts is that researchers using GPS technology should collect data to address their specific a priori formulated research questions, rather than their research being driven by technology. Fortunately, once scientific problems are well defined, there is very little risk that technological advancement results in a loss of focus on hypothesis testing (Boyd et al., 2004).

2.5 GPS Tracking for Wildlife Management and Beyond

The management of data generated by tracking systems, and particularly those GPS-based, is a quite general topic that concerns not only movement ecology but also a wide range of monitoring applications of the so-called moving objects, e.g. people, cars, marine vessels. A lot of different examples for tracking systems are provided by the international project MOVE-COST (http://www.move-cost.info). I decided to work within the framework of wildlife tracking not only because many of my professional collaborations are in this field, but also because it has a primary relevance in either science or practical applications.

From a scientific perspective the role of wildlife tracking is evident: it helps to improve our knowledge of many species, including interactions within and between populations, animal resource use and selection, responses to changing environmental conditions due to climate change or other anthropogenic landscape alterations. On the basis of these individual research components, management policies may be formulated and implemented. However, beyond these ecological applications, there are other contributions that wildlife tracking can provide to improve our lives or encourage a more sustainable use of natural resources.

While in ancient times the knowledge of animal movements and behaviour was mainly important for successful hunting to acquire food, more recently many other sectors can take advantage of detailed information on where animals move and when. Human-wildlife conflicts present a typical example in this context, because tracking data can aid to identify frequently used movement routes at which measures to prevent accidents and other human-wildlife interactions can be implemented (e.g. with virtual fencing: the detection of the location and timing of an animal's path into, or across, geographic objects). In fact in many cases, wherever an interface exists between wildlife habitats and humans-related activity is it likely that conflicts arise. For example, in Europe thisoften happens between farmers and synanthropic species such as wild boar (*Sus scrofa*) that may cause extensive agricultural damages. Furthermore, in regions where humans and large carnivore coexist, e.g. mountainous areas of Italy, also carnivore conservation needs to focus on avoidance of conflicts, because e.g. wolves (*Canis lupus*) and bears (*Ursus arctos*) may prey on livestock or can even be involved in direct aggressive encounters with humans or traffic accidents (Linnell et al., 2001). However, in other parts of the world these interactions may lead to relatively frequent tragic episodes. For instance, in Mozambique 265 people were killed in 27 months (July 2006 to September 2008), mainly by crocodiles (*Crocodylus niloticus*). More details are reported in a paper (see Section 2.5.1) that I had the chance to publish with some colleagues (Dunham et al., 2010). Another major application of wildlife tracking is the identification and possibly prevention of spread of many animal-borne diseases. Typical examples include Lyme disease, bird flu and, to some extent, even Ebola. Tracking data can help identify where infected animals came from, predict where they may go, and assess how they are contracting a certain disease. This information can then be used to mitigate the risk that humans get infected. A less dire field of application for wildlife tracking data is within the recreation sector, including hunting, a widespread activity and often a considerable business, or tourism. For example, in many African countries like Kenya, Tanzania, Zimbabwe and South Africa, tourism linked to wildlife is a major national income source. Finally, moving animals that carry sensors can also be used to collect data on the state of the environment in which they live. This might include the ambient temperature, the distribution of forage or specific physical features of the water column in which a monitored animal is swimming (Boyd et al., 2004).

2.5.1 An Example of Application: Human-Wildlife Conflicts in Mozambique

Abstract of the paper: **Dunham K.M., Urbano F. et al.:** ***Human-wildlife conflict in Mozambique: a national perspective, with emphasis on wildlife attacks on humans*****. Oryx, 2010**.

> *Human–wildlife conflicts are common across Africa. In Mozambique, official records show that wildlife killed 265 people during 27 months (July 2006 to September 2008). Crocodile Crocodylus niloticus, lion Panthera leo, elephant Loxodonta africana and hippopotamus Hippopotamus amphibius caused most deaths but crocodiles were responsible for 66%. Crocodile attacks occurred across Mozambique but 53% of deaths occurred in districts bordering Lake Cabora Bassa and the Zambezi River. Hippopotamus attacks were also concentrated here. Lion attacks occurred mainly in northern Mozambique and, while people were attacked by elephants across the country, 67% of deaths occurred in northern Mozambique. Attacks by lions, elephants or hippopotamuses were relatively rare but additional data will probably show that attacks by these species are more widespread than the preliminary records suggest. Buffalo Syncerus caffer, hyaena Crocuta crocuta and leopard Panthera pardus were minor conflict species. Good land-use planning, a long-term solution to many conflicts, is particularly relevant in Mozambique, where the crocodile and hippopotamus populations of protected areas are often in rivers that border these areas, and cause conflicts outside them, and where people commonly live within protected areas. Poverty may prompt fishermen to risk crocodile attack by entering rivers or lakes. The high incidence of conflicts near Limpopo and South Africa's Kruger National Parks (both within the Great Limpopo Transfrontier Conservation Area) highlights the problems created for people by facilitating the unrestricted movement of wildlife between protected areas across their land.*

Chapter 3

An Innovative Approach in Wildlife Tracking Data Handling

Animal movement is the result of complex and interacting evolutionary mechanisms, uniquely blending gene expression into physiological and behavioral responses. Animal movement has been described as the glue that ties ecological processes together (Turchin, 1998; Nathan et al., 2008) and is an important mechanistic link between ecology and evolution (Cagnacci et al., 2010). Moreover, the growing concern for rapidly changing ecosystems in the face of climate change and other anthropogenic landscape alterations led to a specific interest in the ability of animals to respond to such changes. Consequently, the number of animal tracking studies increased rapidly in the last few years (see Chapter 1), especially those based on animal-borne data sets, i.e. obtained through the deployment of tracking units on individual animals. The innovations in GPS technology (see Chapter 2), combined with systems for remote data-transfer, have particularly favored GPS-based animal telemetry to become a standard in wildlife tracking (Cagnacci et al., 2010). The technological progress that allows ecologists to obtain a huge amount and diversity of empirical animal movement data sets has not been paralleled by an equally rapid development of dedicated tools and procedures to manage and integrate these data sets. Thus, the link between data acquisition and the scientific questions they have the potential to address is often inefficient. In the last five years, this gap has started to be filled gradually and considerable progress has been made not only in terms of tracking technology, but also with respect to the management, visualization, integration and analysis of increasingly large and complex biologging data sets (Rutz and Hays, 2009). Several research groups contributed to advance the state of the art of wildlife tracking data management. Some examples are:

- CSIRO Electronic Tagging Database (Hartog et al., 2009)
- MoveBank (Kranstauber et al., 2011; Dodge et al., 2013)
- OzTrack (Hunter et al., 2013; Dwyer et al., 2015)
- SeaTurtle (http://www.seaturtle.org/)
- STAT (Coyne and Godley, 2005)
- Tagbase (Lam and Tsontos, 2011)
- V-Track (Campbell et al., 2012)
- WRAM (Dettki et al., 2014)

During my research I have been in contact with most of these groups in the spirit of a collaborative approach to the scientific process. This led to a number of shared activities, including the Summer School "Next Generation Data Management in Movement Ecology " organized in 2012 by Leibniz Institute for Zoo and Wildlife Research (IZW, Germany), Swedish University of Agriculture (SLU, Sweden) and Edmund Mach Foundation (FEM, Italy) in Berlin, Germany, with contributions from the Movebank project (US, Germany) and NINA (Norway). This course will be repeated in summer 2015 at FEM in Trento, Italy.

Ideally any movement ecology study should be based on relevant ecological questions that can contribute to theory, and inform conservation and management actions. Once a study has been designed and data collected, only part of the work to answer those questions has been done. The significance of my PhD research lies at this stage of the scientific method. I address i.e how to handle, manage, store and query those data, and how to eventually feed them to analysis tools and test scientific hypotheses. These operations, which are frequently assumed to be of secondary importance within the general goal of answering scientific questions, can instead become overwhelming and hamper the efficiency and consistency of the whole process. The quantity and complexity of GPS and other biologged data require a proper software architecture to be fully exploited and not wasted or, even worse, misused.

I adapt state-of-the-art knowledge and tools on data management to make them applicable for efficient handling of complex biologging data satisfying the data management requirements for their application to wildlife tracking studies. I address the very urgent need for dedicated data repositories and tools for the ever-increasing importance of cooperative projects, data sharing and long term data preservation. Although this research mainly deals with spatial data obtained from individual animals tracked with GPS, most of the conceptual background can be also applied to other sensors or to multi-sensor platforms.

The outputs of my work are two-fold. First, I produced several scientific papers in which general methodological approaches are discussed. These publications especially focus on requirements analysis and data management applications with a special emphasis on the integration of remote sensing-derived environmental information. The second output is the development of innovative tools for wildlife tracking data management based on spatial databases, which have been published as a book (Urbano and Cagnacci, 2014). This work provides a guide for animal ecologists, biologists and wildlife and data managers through a step-by-step procedure to build their own advanced software platforms to manage and process wildlife tracking data. This published work should allow researchers and managers to integrate and harmonize GPS tracking data together with animal characteristics (e.g. age or sex), environmental data sets, including remote sensing image time series, and other biologged data, such as acceleration data. It is based on the open source PostgreSQL/PostGIS spatial database. It shows how the powerful R statistical environment can be integrated into the software platform, either connecting the database with R, or embedding the same tools in the database through the PostgreSQL extension Pl/R. The client/server architecture allows users to remotely connect a number of software applications that can be used as a database front end, including GIS software and WebGIS. Each chapter of the book outlines a real-world data management and processing problem that is discussed in its biological context. Then, solutions are proposed and exemplified through ad hoc SQL code, progressively exploring the potential of spatial database functions applied to the respective wildlife tracking case. Finally, wildlife tracking data management issues are discussed in the increasingly widespread framework of collaborative science and data sharing.

The content of this chapter is an extended summary of the work I published during my research and that are listed in Appendix 1. Each section begins with a short introduction followed by the collection of abstracts of my corresponding published papers and book chapters that are the reference for a complete discussion of the results of my research. Particularly, Section 3.1 reports an analysis of the requirements of animal movement-related scientific questions and of wildlife tracking data that is the basis for the discussion of the proposed data management platform. Section 3.2 illustrates how this platform can be used to exploit tracking data by joining with other environmental information. The main focus lies on remote sensing images that can be used to describe habitat changes within and between years (i.e. vegetation indices time series). In this context, innovative methods to join data management and data analysis are proposed. Finally, Section 3.3 introduces the case study of the EURODEER project where many of the concepts illustrated in Sections 3.1 and 3.2 find application.

It is important to mention that the whole research was based on an open approach. One of the main implications is that all results were made publicly available as much as possible and that the proposed software platform is open source. In fact, all tools and methodological approaches are developed upon PostgreSQL and its spatial extension PostGIS, although they can be adapted to work on other software platforms. There are many reasons that support the choice of PostgreSQL/PostGIS, for example:

- both are free and open source, which also means that any financial resources available to scientific projects can be used for customisation instead of software licences, especially if funds are limited;
- PostgreSQL is an advanced and widely used database system and offers many features useful for animal movement data management;
- PostGIS is currently one of the most, if not the most, advanced spatial database extensions available and its development is quickly progressing;
- PostGIS includes support for raster data, a dedicated geography spatial data type, topology and networks, and has a huge library of spatial functions;
- there is a wide, active and very supportive community for both PostgreSQL and PostGIS;
- there is very good documentation for both PostgreSQL and PostGIS (manuals, tutorials, books, wiki, blogs);
- PostgreSQL and PostGIS widely implement standards, which make them highly interoperable with numerous other tools for data management, analysis, visualisation and dissemination;
- many other research projects related to wildlife tracking data management are using the same software platform (e.g. Movebank, OzTrack).

3.1 Spatial Database for Managing Tracking Data

The main component of my research focusses on the adaptation of a (spatial) relational database framework for management (i.e. acquisition, storage, processing, sharing) of animal movement data. The first step of my work was a requirements analysis based on user needs and data characteristics. This process was the onset of my collaboration with movement ecology experts (Cagnacci and Urbano, 2008), which continued in the following years until a clear framework was defined (Urbano et al., 2010). The results of this work were then further extended and structured in a book (Urbano and Cagnacci, 2014), where I propose solutions to cope with the *a priori* identified requirements. In summary, this research followed a clearly outlined path. The initial review of opportunities and challenges that are posed by GPS tracking from a data management perspective (Section 3.1.1) lead to the identification of a spatial database as the best technical tool to meet the requirements (Section 3.1.2). This was the basis for the development of an information system for wildlife tracking that includes a spatial database data model and functionalities to manage the entire data acquisition process (Section 3.1.3). The core database structure is then extended to integrate data from other biologging sensors, in particular acceleration data (Section 3.1.4).

3.1.1 Requirements Analysis

Abstract of the paper: **Urbano F., Cagnacci F., et al.: *Wildlife tracking data management: a new vision*. Philosophical Transactions of the Royal Society B. 365 (1550): 2177-2185, July 2010.**

To date, the processing of wildlife location data has relied on a diversity of software and file formats. Data management and the following spatial and statistical analyses were undertaken in multiple steps, involving many time-consuming importing/exporting phases. Recent technological advancements in tracking systems have made large, continuous, high-frequency datasets of wildlife behavioural data available, such as those derived from the global positioning system (GPS) and other animal-attached sensor devices. These data can be further complemented by a wide range of other information about the animals' environment. Management of these large and diverse datasets for modelling animal behaviour and ecology can prove challenging, slowing down analysis and increasing the probability of mistakes in data handling. We address these issues by critically evaluating the requirements for good management of GPS data for wildlife biology. We highlight that dedicated data management tools and expertise are needed. We explore current research in wildlife data management. We suggest a general direction of development, based on a modular software architecture with a spatial database at its core, where interoperability, data model design and integration with remote-sensing data sources play an important role in successful GPS data handling.

Abstract of the chapter: **Dettki H., Urbano F. et al.: *Wildlife Tracking Data Management: Chances Come from Difficulties* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

In recent years, new wildlife tracking and telemetry technologies have become available, leading to substantial growth in the volume of wildlife tracking data. In the future, one can expect an almost exponential increase in collected data as new sensors are integrated into current tracking systems. A crucial limitation for efficient use of telemetry data is a lack of infrastructure to collect, store and efficiently share the information. Large data sets generated by wildlife tracking equipment pose a number of challenges: to cope with this amount of data, a specific data management approach is needed, one designed to deal with data scalability, automatic data acquisition, long-term storage, efficient data retrieval, management of spatial and temporal information, multi-user support and data sharing and dissemination. The state-of-the-art technology to meet these challenges are relational database management systems

(DBMSs), with their dedicated spatial extension. DBMSs are efficient, industry-standard tools for storage, fast retrieval and manipulation of large data sets, as well as data dissemination to client programs or Web interfaces. In the future, we expect the development of tools able to deal at the same time with both spatial and temporal dimensions of animal movement data, such as spatiotemporal databases.

3.1.2 A Technical Solution: Spatial Database

Abstract of the chapter: **Urbano F., Dettki H.: *Storing Tracking Data in an Advanced Database Platform (PostgreSQL)* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

The state-of-the-art technical tool for effectively and efficiently managing tracking data is the spatial relational database. Using databases to manage tracking data implies a considerable effort for those who are not already familiar with these tools, but this is necessary to be able to deal with the data coming from the new sensors. Moreover, the time spent to learn databases will be largely paid back with the time saved for the management and processing of the data. In this chapter, you are guided through how to set up a new database in which you will create a table to accommodate the test GPS data sets. You create a new table in a dedicated schema. We describe how to upload the raw GPS data coming from five sensors deployed on roe deer in the Italian Alps into the database and provide further insight into time-related database data types and into the creation of additional database users. The reference software platform used is the open source PostgreSQL with its spatial extension PostGIS. This tool is introduced with its graphical interface pgAdmin. All the examples provided (SQL code) and technical solutions proposed are tuned on this software, although most of the code can be easily adapted for other platforms. The book is focused on the applications of spatial databases to the specific domain of movement ecology: to properly understand the content of this guide and to replicate the proposed database structure and tools, you will need a general familiarity with GIS, wildlife tracking and database programming.

3.1.3 Designing an Information System for Wildlife Tracking

Abstract of the chapter: **Urbano F.: *Extending the Database Data Model: Animals and Sensors* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

GPS positions are used to describe animal movements and to derive a large set of information, for example, about animals' behaviour, social interactions and environmental preferences. GPS data are related to (and must be integrated with) many other sources of information that together can be used to describe the complexity of movement ecology. This can be achieved through proper database data modelling, which depends on a clear definition of the biological context of a study. Particularly, data modelling becomes a key step when database systems manage many connected data sets that grow in size and complexity: it permits easy updates of the database structure to accommodate the changing goals, constraints and spatial scales of studies. In this chapter's exercise, you will extend your database with two new tables to *integrate ancillary information useful to interpreting GPS data: one for GPS sensors and the other for animals.*

Abstract of the chapter: **Urbano F.: *From Data to Information: Associating GPS Positions with Animals* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

When position data are received from GPS sensors, they are not explicitly associated with any animal. Linking GPS data to animals is a key step in the data management process. This can be achieved using the information on the deployments of GPS sensors on animals (when sensors started and ceased to be deployed on the animals). In the case of a continuous data flow, the transformation of GPS positions into animal locations must be automated in order to have GPS data imported and processed in real-time. In the exercise for this chapter, you extend the database built in Chaps. 2 and 3 with two new tables, gps-sensors-animals and gps-data-animals, and a set of dedicated database triggers and functions that add the necessary tools to properly manage the association of GPS positions with animals.

Abstract of the chapter: **Urbano F., Basille M.: *Spatial is not Special: Managing Tracking Data in a Spatial Database* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

A wildlife tracking data management system must include the capability to explicitly deal with the spatial properties of movement data. GPS tracking data are sets of spatiotemporal objects (locations), and the spatial component must be properly managed. You will now extend the database built in Chaps. 2, 3 and 4, adding spatial functionalities through the PostgreSQL spatial extension called PostGIS. PostGIS introduces spatial data types (both vector and raster) and a large set of SQL spatial functions and tools, including spatial indexes. This possibility essentially allows you to build a GIS using the capabilities of relational databases. In this chapter, you will start to familiarise yourself with spatial SQL and implement a system that automatically transforms the GPS coordinates generated by GPS sensors from a pair of numbers into spatial objects.

Abstract of the paper: **Cagnacci F., Urbano F.: *Managing wildlife: a spatial information system for GPS collars data analysis and modelling*. Environmental Modelling and Software, 2008.**

ISAMUD (Integrated System for Analysis and Management of Ungulate Data) is an integrated and modular software platform developed to manage GPS collar data for wildlife management. It is based on an open source spatial database (PostgreSQL and PostGIS) and includes open source data management, geo-statistical analysis and Web services modules (R, QGIS, GRASS, MapServer, Ka-Map) and a proprietary database front-end (MS Access).

It is able to store, retrieve, update, analyze, visualize and disseminate GPS telemetry data in an efficient and consistent way, with a high degree of automatization.

3.1.4 Integrating Data from other Biologging Sensors

Abstract of the chapter: **Berger A., Dettki H., Urbano F.: *Deciphering Animals' Behaviour: Joining GPS and Activity Data* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

In the previous chapters, you have exclusively worked with GPS position data. We showed how to organise these data in databases, how to link them to environmental data and how to connect them to R for further analysis. In this chapter, we introduce an example of data recorded by another type of sensor: acceleration data, which can be measured by many tags where they are associated with the GPS sensors and are widely used to interpret the behaviour of tagged animals. The general structure of these data and an overview of possibilities for analysis are given. In the exercise for this chapter, you will learn how to integrate an acceleration data set into the database created in the previous chapters and link it with other information from the database. At the end, the database is extended with acceleration data and with an automated procedure to intersect these layers with GPS positions.

3.2 From Geographical Space to the Animal's Ecological Space

Once a general framework for managing tracking data was defined, I continued my research by including spatial ancillary information on the environment into this optimized platform. External factors such as land cover/use, vegetation status, weather and human disturbance affect the movement of animals (Dodge et al., 2013). Therefore, the integration of environmental information, often characterized by large volumes of raw data generated by heterogeneous sources in different formats, is essential to explore animal behaviour and understand the ecological relationships that can be revealed by tracking data. Spatial databases can manage these different data sets in a unified framework, defining spatial and non-spatial relationships that simplify the analysis of the interactions between animals and their habitat. The result is that animal locations are automatically transformed from a simple set of numbers (coordinates) to complex multi-dimensional (spatial) objects that define the individual in time and space in its environment (Section 3.2.1). This approach can be further improved considering the environmental variables that are dynamic, i.e. that change at a comparable temporal scale of the animal movement. This is possible using remote sensing image time series when proper statistical and computational methods and software tools for data processing are available. An example is the identification of the phenological periods of vegetation used by animals as forage. This requires a pixel-based analysis of vegetation indices (e.g. NDVI) temporal profiles. I worked on this topic contributing to the development of a software tool specifically designed to deal with image time series of remote sensing information related to vegetation. Moreover, I contributed to define a set of algorithms based on temporal series of vegetation indices that can help to monitor and forecast vegetation conditions. The main focus was on the monitoring of crops and pastures, but the results can be also applied in the context of wildlife research (Section 3.2.2). The next step was the development of analytical tools based on spatial database functionalities for advanced spatial modelling. Different representations of tracking data can be used to explore specific aspects of animal' movements (e.g. trajectories, raster surfaces of probability density, set of points, home range polygons, tabular statistics), which can be integrated into the database framework (Section 3.2.3). One key step in this process is the automatic identification of outliers that can affect analysis, leading to biased inferences and possibly even erroneous wildlife management/conservation suggestions. Therefore, I created some database routines for an automatic screening of suspicious locations (Section 3.2.4). The last extension, and more recent advancement, was the integration of statistical environments into the database platform. The possibility to use a statistical environment engine and libraries inside the database has many advantages. For example it avoids unnecessary data replication, allows the use of a single SQL interface for complex scripts also involving statistical commands and offers a tight integration of data analysis and management processes. I explored these possibilities using Pl/R, a loadable procedural language that allows the use of R software directly within PostgreSQL (Section 3.2.5).

3.2.1 Integrating Information on Environmental Factors

Abstract of the chapter: **Urbano F., Basille M., Racine P.: *From Points to Habitat: Relating Environmental Information to GPS Positions* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

Animals move in and interact with complex environments that can be characterised by a set of spatial layers containing environmental data. Spatial databases can manage these different data sets in a unified framework, defining spatial and non-spatial relationships that simplify the analysis of the interaction between animals and their habitat. A large set of analyses can be performed directly in the database with no need for dedicated GIS or statistical software. Such an approach moves the information content managed in the database from a geographical space to an animal's ecological space. This more comprehensive model of the animals' movement ecology reduces the distance between physical reality and the way data are structured in the database, filling the semantic gap between the scientist's view of biological systems and its implementation in the information system. This chapter shows how vector and raster layers can be included in the database and how you can handle them using (spatial) SQL. The database built so far in Chaps. 2, 3, 4 and 5 is extended with environmental ancillary data sets and with an automated procedure to intersect these layers with GPS positions.

3.2.2 Monitoring Animals in a Dynamic Environment: Remote Sensing Image Time Series

Abstract of the chapter: **Basille M., Urbano F.: *Tracking Animals in a Dynamic Environment: Remote Sensing Image Time Series* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

This chapter looks into the spatiotemporal dimension of both animal tracking data sets and the dynamic environmental data that can be associated with them. Typically, these geographic layers derive from remote sensing measurements, commonly those collected by sensors deployed on earth-orbiting satellites, which can be updated on a monthly, weekly or even daily basis. The modelling potential for integrating these two levels of ecological *complexity (animal movement and environmental variability) is huge and comes from the possibility to investigate processes as they build up, i.e. in a full dynamic framework. This chapter's exercise will describe how to integrate dynamic environmental data in the spatial database and join to animal locations one of the most used indices for ecological productivity and phenology, the normalised difference vegetation index (NDVI) derived from MODIS.*

Abstract of the paper: **Eerens H., Urbano F., et al.: *An image time series processing software for agriculture monitoring*. Environmental Modelling and Software, 2014.**

Given strong year-to-year variability, increasing competition for natural resources, and climate change impacts on agriculture, monitoring global crop and natural vegetation conditions is highly relevant, particularly in food insecure areas. Data from remote sensing image series at high temporal and low spatial resolution can help to assist in this monitoring as they provide key information in near real-time over large areas. The SPIRITS software, presented in this paper, is a stand-alone toolbox developed for environmental monitoring, particularly to produce clear and evidence-based information for crop production analysts and decision makers. It includes a large number of tools with the main aim of extracting vegetation indicators from image time series, estimating the potential impact of anomalies on crop production and sharing this information with different audiences. SPIRITS offers an integrated and flexible analysis environment with a user-friendly graphical interface, which allows sequential tasking and a high level of automation of processing chains. It is freely distributed for non-commercial use and extensively documented.

Abstract of the paper: **Meroni M., Urbano F., et al.: *Early detection of biomass production deficit hot-spots in semi-arid environment using FAPAR time series and a probabilistic approach*. Remote Sensing of Environment, 2014.**

Early warning monitoring systems in food-insecure countries aim to detect unfavourable crop and pasture conditions as early as possible during the growing season. This manuscript describes a procedure to estimate the probability of experiencing an end-of-season biomass production deficit during the on-going season based on a statistical analysis of Earth Observation data. A 15-year time series of the Fraction of Absorbed Photosynthetically Active Radiation from the SPOT-VEGETATION instrument is used to characterize the climatological development of vegetation, its variability and its current status. Forecasts of overall seasonal performances, expressed in terms of the probability of experiencing a critical deficit at the end of the growing season, are updated regularly whenever a new satellite observation is made available. Results and performances of the method are discussed for croplands and pastures in the Sahel.

Abstract of the paper: **Meroni M., Urbano F., et al.: *A phenology-based method to derive biomass production anomalies for food security monitoring*. International Journal of Remote Sensing, 2013.**

> *Monitoring vegetation conditions is a critical activity for assessing food security in the Horn of Africa. Remote sensing from space offers a unique opportunity to obtain consistent and timely information over large and often inaccessible areas where field observations are scattered, non-homogenous, or frequently unavailable. In this study we outline a method to assess objectively the performance and characteristics of seasonal vegetation development solely on the basis of time series of the fraction of absorbed photosynthetically active radiation (FAPAR) derived from Satellite Pour l'Observation de la Terre SPOT-VEGETATION (SPOT-VGT) imagery. Key phenological indicators such as the start and end of growing periods are derived from a statistical analysis of the time series to characterize the spatial and temporal evolution of successive seasons. These indicators are then utilized to compute a proxy of the seasonal gross primary production (GPP) as the cumulative FAPAR during the growing season. Vegetation condition and associated risk of food deficit for specific seasons and locations are finally derived from the comparison of the seasonal GPP proxy with its average value computed over the whole time series. The impact on vegetation of the severe drought experienced by the Horn of Africa between late 2010 and late 2011 is discussed.*

3.2.3 Wildlife Tracking Data Modelling and Analysis

Abstract of the chapter: **Urbano F., Basille M., Racine P.: *Exploring Tracking Data: Representations, Methods and Tools in a Spatial Database* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

> *The objects of movement ecology studies are animals whose movements are usually sampled at more-or-less regular intervals. This spatiotemporal sequence of locations is the basic, measured information that is stored in the database. Starting from this data set, animal movements can be analysed (and visualised) using a large set of different methods and approaches. These include (but are not limited to) trajectories, raster surfaces of probability density, points, (home range) polygons and tabular statistics. Each of these methods is a different representation of the original data set that takes into account specific aspects of the animals' movement. The database must be able to support these multiple representations of tracking data. In this chapter, a wide set of methods for implementing many GPS tracking data representations into a spatial database (i.e. with SQL code and database functions) are introduced.*

3.2.4 Detection and Management of Outliers

Abstract of the chapter: **Urbano F., Basille M., Cagnacci F.: *Data Quality: Detection and Management of Outliers* in *Spatial Database for GPS Wildlife Tracking Data*, 2014, Eds. Urbano F., Cagnacci F., Springer.**

> *Tracking data can potentially be affected by a large set of errors in different steps of data acquisition and processing. Erroneous data can heavily affect analysis, leading to biased*

inference and misleading wildlife management/conservation suggestions. Data quality assessment is therefore a key step in data management. In this chapter, we especially deal with biased locations, or "outliers". While in some cases incorrect data are evident, in many situations, it is not possible to clearly identify locations as outliers because although they are suspicious (e.g. long distances covered by animals in a short time or repeated extreme values), they might still be correct, leaving a margin of uncertainty. In this chapter, different potential errors are identified and a general approach to managing outliers is proposed that tags records rather than deleting them. According to this approach, practical methods to find and mark errors are illustrated.

3.2.5 Advanced Statistical Tools: Integrating R Statistics into the Database

Abstract of the chapter: **Basille M., Urbano F., Conway J.:** ***A Step Further in the Integration of Data Management and Analysis: Pl/R*** **in** ***Spatial Database for GPS Wildlife Tracking Data*****, 2014, Eds. Urbano F., Cagnacci F., Springer.**

This chapter introduces the Pl/R extension, a very powerful alternative to integrate the features offered by R in the database in a gapless workflow. Pl/R is a loadable procedural language that allows the use of the R engine and libraries directly inside the database, thus embedding R scripts into SQL statements and database functions and triggers. Among many advantages, Pl/R avoids unnecessary data replication, allows the use of a single SQL interface for complex scripts involving R queries and offers a tight integration of data analysis and management processes into the database. In this chapter, you will have a basic overview of the potential of Pl/R for the study of GPS locations. You will be introduced to the use of Pl/R, starting with exercises involving simple calculations in R (logarithms, median and quantiles), followed by more elaborated exercises designed to compute the daylight times of a given location at a given date, or to compute complex home range methods.

3.3 Study Case: the EURODEER Project

In science the primary motivation for developing collaborations based on data sharing is to increase research productivity. More and more scientific outcomes from collaborative approaches are emerging from a number of large research projects. This is quickly becoming a consolidated practice in many research domains (e.g. physics, genetics, astronomy, earth observation, oceanography), because it is now evident that diverse and long-term data contributes to better science, producing rapid research breakthroughs that otherwise would not occur. Nevertheless, the scientific community is far from fully exploiting the potential offered by data sharing (Costello, 2009). One reason for this are technical aspects. Although technological barriers to connect different information systems are diminishing, problems such as the availability of dedicated data e-infrastructures or the definition and use of data and metadata standards remain. However, unfortunately also the general attitude of scientists, who are not always in favour of collaborative research and data sharing, often hampers progress. One of the reasons is that scientific contributions by individual researchers are very strongly acknowledged within the scientific community (e.g. in progress reports or for the allocation of research funding), but an adequate science reward system is not yet fully in place to stimulate subsequent integration of their data within larger collaborative research studies to maximize returns from research funding (Cassey and Blackburn, 2006). There is also considerable resistance due to the additional costs and time requirements that data sharing implies (Tenopir et al., 2011). Lack of proper technical skills in data management represents a further obstacle. In contrast, in many countries governments are promoting strict rules to force publication of data whenever researchers are funded by public institutions (e.g. National Science Foundation in the USA). Many peer-reviewed journals require researchers to make any information needed to understand and replicate published results available (e.g. Nature, Science, Royal Society Publishing), either by depositing the data in a public repository or making it freely available upon request. Although this remains frequently disregarded by authors (Savage and Vickers, 2009), requests for data sharing are increasing in the main journals (Guralnick et al., 2009; Nelson, 2009; Hanson et al., 2011; Reichman et al., 2011) and in the scientific community in general (e.g. http://scientificdatasharing.com, http://www.okfn.org).

Within the field of biodiversity, data sharing can bring enormous advantages to research, opening the door to long term, multi-species, large scale studies (Carpenter et al., 2009). In collaborative projects, ecological issues can be investigated at both local and global scales with an integrative approach. This would be otherwise impossible within the framework of individual projects. These potential advantages are well recognized by many biodiversity researchers (e.g. Parr and Cummings, 2005; Jones et al., 2006; Scholes et al., 2008; Queenborough et al., 2010). As a result, a number of national and international databases for promoting ecological data access and collaborative research emerged and are generating an increasing number of publications (e.g. National Biodiversity Information Infrastructure, http://www.nbii.gov; the National Biodiversity Network, http://www.nbn.org.uk; the Global Biodiversity Information Facility, http://www.gbif.org).

In the specific domain of wildlife tracking a number of initiatives have already been undertaken (e.g. Movebank, OBIS, Seamap, SeaTurtle, WRAM, OzTrack), but we are still far from an established practise of data sharing and movement ecology papers from collaborative projects are still rare (Davidson, 2014), despite the manifold advantages outlined above. As discussed in Chapter 1, deploying sensors on animals is often expensive, both in terms of capture logistics and actual cost of tracking devices. Further, it creates some amount of stress for the marked animals. These costs should pose financial and even moral incentives to maximize the effective use of animal-borne data. Moreover, many large scale questions, such as evaluating the effects of climate and land use change on animal distributions, can be properly addressed only by studying multiple populations, or by integrating data from several species or time periods. Data requirements for such studies are virtually impossible for any single research institution to meet, and can only be achieved by collaborative research and data sharing (Whitlock, 2011).

Herein I present a case study on the European roe deer, which is a very well studied species. It plays a crucial role in European ecosystems and is a very good model species due to its high ecological plasticity and wide distribution. It is evident to researchers involved in roe deer studies that an easily accessible database populated with joined movement data from different populations would strongly support the attempt to develop a complete picture of roe deer biology. This is the premise that led to the development of the EUropean ROe DEER (EURODEER) project. EURODEER is essentially an open community based on a collaborative process of data sharing to produce better science. The project started in 2008 as an informal collaboration between Edmund Mach Foundation (Trento, Italy) and University C. Bernard Lyon 1 (France) to share knowledge on wildlife tracking data management. At the moment, 29 European research groups participate the EURODEER project (http://www.eurodeer.org), and 22 contribute with GPS, VHF or activity (i.e. from accelerometers) data. The core of the EURODEER project is the database that stores and processes the shared data of roe deer movements, metadata (captures, individuals) and ancillary environmental information (MODIS snow, Modis NDVI and Spot Vegetation FAPAR satellite image time series; Corine land cover; administrative boundaries; digital elevation model derived parameters). Researchers within the collaboration use the database to study e.g. variation in animal behavioural ecology along environmental gradients and population responses to specific conditions, such as habitat changes, impact of human activities or different hunting regimes. I carried out the requirements analysis and the design and development of the platform. The software platform is based on PostgreSQL/PostGIS, with a large set of functions specifically developed to deal with tracking data in a modular client/server architecture (Urbano et al., 2010). Data are stored in the server database where client software applications remotely get the information and store back the results of analysis. Task-oriented software are used to manage the data flow, processing and analysis (i.e. PhpPgAdmin, PgAdmin, GRASS, R, QGIS, ArcGIS). The EURODEER information system is partially derived from the ISAMUD system (Cagnacci and Urbano, 2008). A major component of the work was the definition of standards for data and metadata in terms of both structure and semantics through a domain specific controlled vocabulary (Jones et al., 2006; Michener, 2006; Madin et al., 2007). This work is still under development inside the EURODEER community and substantial inputs can be expected from the broader animal movement community in the future. Currently, further improvements are related to the inclusion of movement data of red deer (*Cervus elaphus*) and wild board (*Sus scrofa*) and the extension of meta-information that are valuable data sets per se (e.g. population data).

The ultimate goal of EURODEER is to share data and knowledge on animal movement analysis to advance science in this discipline. I also contributed to the first scientific outputs of the project based on the EURODEER database. Until now, three papers have been published: Cagnacci et al. (2011), Morellet et al. (2013), Debeffe et al. (2014), while others are currently under development.

Abstract of the paper: **Cagnacci F., Urbano F., et al.: *Partial migration in roe deer: migratory and resident tactics are end points of a behavioural gradient determined by ecological factors*, Oikos, 2011.**

> *Ungulate populations exhibiting partial migration present a unique opportunity to explore the causes of the general phenomenon of migration. The European roe deer Capreolus capreolus is particularly suited for such studies due to a wide distribution range and a high level of ecological plasticity. In this study we undertook a comparative analysis of roe deer GPS location data from a representative set of European ecosystems available within the EURODEER collaborative project. We aimed at evaluating the ecological factors affecting migration tactic (i.e. occurrence) and pattern (i.e. timing, residence time, number of migratory trips). Migration occurrence varied between and within populations and depended on winter severity and topographic variability. Spring migrations were highly synchronous, while the timing of autumn migrations varied widely between regions, individuals and sexes. Overall, roe deer were faithful to their summer ranges, especially males. In the absence of extreme and predictable winter conditions, roe deer seemed to migrate opportunistically, in response to a tradeoff between the costs of residence in spatially separated ranges and the costs of migratory movements. Animals performed numerous trips between winter and*

summer ranges which depended on factors influencing the costs of movement such as between-range distance, slope and habitat openness. Our results support the idea that migration encompasses a behavioural continuum, with one-trip migration and residence as its end points, while commuting and multi-trip migration with short residence times in seasonal ranges are intermediate tactics. We believe that a full understanding of the variation in tactics of temporal separation in habitat use will provide important insights on migration and the factors that influence its prevalence.

Abstract of the paper: **Morellet N., Urbano F. et al.:** ***Seasonality, weather, and climate affect home range size in roe deer across a wide latitudinal gradient within Europe*. Journal of Animal Ecology, 2013.**

Ungulate populations exhibiting partial migration present a unique opportunity to explore the causes of the general phenomenon of migration. The European roe deer (Capreolus capreolus) is particularly suited for such studies due to a wide distribution range and a high level of ecological plasticity. In this study we undertook a comparative analysis of roe deer GPS location data from a representative set of European ecosystems available within the EURODEER collaborative project. We aimed at evaluating the ecological factors affecting migration tactic (i.e. occurrence) and pattern (i.e. timing, residence time, number of migratory trips). Migration occurrence varied between and within populations and depended on winter severity and topographic variability. Spring migrations were highly synchronous, while the timing of autumn migrations varied widely between regions, individuals and sexes. Overall, roe deer were faithful to their summer ranges, especially males. In the absence of extreme and predictable winter conditions, roe deer seemed to migrate opportunistically, in response to a tradeoff between the costs of residence in spatially separated ranges and the costs of migratory movements. Animals performed numerous trips between winter and summer ranges which depended on factors influencing the costs of movement such as between-range distance, slope and habitat openness. Our results support the idea that migration encompasses a behavioural continuum, with one-trip migration and residence as its end points, while commuting and multi-trip migration with short residence times in seasonal ranges are intermediate tactics. We believe that a full understanding of the variation in tactics of temporal separation in habitat use will provide important insights on migration and the factors that influence its prevalence.

Abstract of the paper: **Debeffe L., Urbano F., et al.:** ***A one night stand? Reproductive excursions of female roe deer as a breeding dispersal tactic*. Oecologia, 2014.**

Breeding dispersal, defined as the net movement between successive breeding sites, remains a poorly understood and seldom reported phenomenon in mammals, despite its importance for population dynamics and genetics. In large herbivores, females may be more mobile during the breeding season, undertaking short-term trips (excursions) outside their normal home

range. If fertilisation occurs, leading to gene flow of the male genome, this behaviour could be considered a form of breeding dispersal from a genetic point of view. Here, we investigated ranging behaviour of 235 adult roe deer using intensive GPS monitoring in six populations across Europe within the EURODEER initiative. We show that excursions are common from June to August among females, with 41.8% (vs. 18.1% of males) making at least one excursion. Most individuals performed only one excursion per season and departure dates for females were concentrated in time, centred on the rutting period, suggesting a link with reproduction. The distance females travelled during excursions was significantly greater than the site-specific average diameter of a male home range, while travel speed decreased once they progressed beyond this diameter, indicating search behaviour or interaction with other male(s) outside the resident male's territory. Because adults are normally highly sedentary, the potential for mating with relatives is substantial; hence, we conclude that rut excursions could be an alternative tactic enabling females to avoid mating with a closely related male. To understand better the ultimate drivers at play, it will be crucial to explore the genetic causes and consequences of this behaviour.

Chapter 4

Conclusions

Until today data management remains a poorly implemented aspect in ecological studies, probably as a result of the general reluctance to change work habits and undertake the initial costs for workflow and software updates. However, parallel to the the advent of GPS tracking in the last 15 years, researchers in the field of movement ecology quickly realized that data management with dedicated tools and expertise is essential. Although the adoption of proper approaches to data handling in this scientific domain is a slow process, the advancements achieved in the last years are evident and confirmed by the growing number of papers recently published on this topic. In this dynamic context characterized by fast improvements in both tracking sensors and data management technology, I aimed to contribute by joining scientific requirements and available technology. With the outputs of my research I also hope to address challenges that the next generation of wildlife monitoring sensors will pose to scientists. The interest in this topic is demonstrated by the impact of the published work. For example, at 31/12/2014 the paper Urbano et al. (2010) was requested (downloaded or visualized in full) by more than 8,500 persons (source: Philosophical Transactions B metrics available on the journal's website) and in the first 4 months the book (Urbano and Cagnacci, 2014) was acquired by more than 3,000 researchers (source: Springer editors, personal communication).

The underlying motivation for my PhD research was that good practice management of GPS-based locations is an essential step towards better science. Proving this statement empirically is difficult, although the best evidence is the enhanced efficiency and consistency in results. In my work, together with my colleagues, I proposed a spatial database framework as reference tool to build efficient and effective information systems for management and analysis of animal movement data. I contributed to develop methodological approaches and tools to optimize data handling and particularly the integration of GPS data with other sensor data and environmental information derived from remote sensing. This innovative approach offers the opportunity to model location data as objects characterizing the presence of individuals in space and time within their habitat.

I think that the intrinsic consistency and integrity of spatial databases represents a necessary infrastructure for rigorous science per se, preventing error propagation, optimizing performance of analysis and improving robustness of inferences. In particular, this favours the transition from simple descriptive approaches towards mechanistic models with higher explanatory and predictive power (e.g. Millspaugh and Marzluff, 2001; Morales et al., 2010; Smouse et al., 2010), focusing wildlife research on biological, rather than statistical, significance (Johnson, 1999; Otis and White, 1999; Ropert-Coudert and Wilson, 2005).

This field of research is inherently linked to the very dynamic technological developments of sensors for wildlife and environmental monitoring. Data management in movement ecology is still in its early stage and in the near future it can be easily placed in the broader framework of "Big Data". In fact, It shares the same challenges of all big data that come from the increasing volume of data recorded, diversity of variables monitored, and frequency of acquisition. The challenges include capture, curation, sharing, storage, analysis, visualization, and, in some cases, privacy violations. The diversity of tracking devices and data formats are not only complicating integration and synthesis of electronic tagging data but are already potentially threatening the integrity and longer-term access to these valuable data sets (Lam and Tsontos, 2011). These risks will continue to grow in the next years.

Two main kinds of advancements will probably characterize wildlife tracking in the future. In the short term, we can expect a rapid optimization of many components of satellite-based tracking systems, which benefit from the large commercial market driving GPS development. There is a clear trend towards GPS receivers becoming smaller, operating at lower voltages, consuming less power and exhibiting reduced time to first fix (TTFF) (Tomkiewicz et al., 2010). Also memory capacity will increase and batteries will be improved. All these elements contribute to extend the number of species and individuals that can be monitored and the quality and quantity of positional data collected. Concurrently new GNSS, including the Russian GLONASS, European Galileo and Chinese Compass are emerging. These systems can potentially be used for animal positioning and can provide higher precision locations and reduce acquisition failure. Sensor networks are another interesting technology that will impact animal and environmental monitoring in the coming years. Sensor networks are able to integrate data analysis procedures into the network itself, identify outliers, alter sampling regimes, and ultimately control experimental infrastructure (Collins et al., 2006). At the same time they pose new data analysis and management challenges. The process of integration of GPS and activity data recorders using body accelerometers is going to continue and improved analytical methods are expected to automatically identify animal behaviour from semantic segmentation of trajectories (Calenge et al., 2009; Hebblewhite and Haydon, 2010). Other advances in tracking data management are dealing with the urgent need for integration of large sets of data from different research groups. In fact, many research questions in ecology, particularly those addressing global change, require large, long-term data sets that cannot be collected by any one research group alone. This implies the necessity of shared data infrastructures for tracking data and their integration into federation of databases or broader e-infrastructures. At the same time this reveals the urgency of a standardized approach to animal tagging data management both for tracking devices and for data storage and processing. For example, sensor data formats are often proprietary and data can only be accessed with third-party software. Therefore a platform needs to develop specific pieces of software for each sensor vendor to integrate these components and retrieve data from its source. This limits the possibility to create information systems managing different sensors and brands, which is instead a common situation for many research groups. The integration of different tracking data sets and the growing demand for data sharing highlight another key issue: together with the data a large set of metadata must be standardized and properly stored. In many cases, these metadata are data sets on their own, as for example information on captures, individuals, and populations. This information is very important as it provides additional explanatory variables and allows researchers to put their movement data into a broader perspective to answer their scientific questions. However, the definition of standards and protocols is complicated due to the fact that many meta-information are species-specific, making the integration of data from different species very complex. We can expect that the scientific community will invest in this direction. From a technical point of view, in the next few years wildlife tracking data management will benefit from the development of the spatio-temporal databases, moving the perspective from a temporal sequences of locations to a single moving object (the animal). Moreover, a natural extension in management and analysis approaches is a better integration of 3D coordinates, where horizontal coordinates (i.e. latitude and longitude) are properly complemented by altitude for avian species or depth for marine species. In general, it can be foreseen that the animal movement communities dealing with the different domains (terrestrial, marine, avian) that were traditionally quite separated from one another, will converge and share challenges and innovations. This can be expected for example in the development of visualization and analysis techniques optimized for very large data sets (Renso et al., 2013; Pelekis and Theodoridis, 2014) and a more explicit and quantitative measure of the errors to be included in the analysis (Frair et al., 2010). Finally, the new generation of satellite sensors (e.g. Landsat 8, Sentinel) are already or are going to provide information with very high temporal and spatial resolution on the environment in which animals move. Ideally, these data should be integrated into the wildlife tracking information system, requiring additional functions to manage large image time series.

In the medium and long term it is more difficult to anticipate the technical developments and their impact from a data management perspective. When justified by the scientific questions underpinning empirical studies, the use of multi-sensor platforms deployed on individual animals can be a powerful tool to obtain a complex and diversified picture of the animal and its environment. With the miniaturization of technology and adaptation of devices to an increasing number of species, multi-sensor platforms and their resulting data sets are likely to be even more common in the future. This offers the possibility to gain increasingly comprehensive insights into the biology of animals thanks to the simultaneous measurement of several variables, more sophisticated on-board data processing and added functionality of instruments. There is a clear trend that points to an ever broader range of sensors and variables measured. The presence of multiple sources of information (i.e. the sensors) fitted on the same animal does not represent a challenge per se, as long as each type of information is consistently linked to one specific individual and joined to the other data sources. However, this requires a highly dedicated and consistent management structure. The increase in data sets size and complexity might require a new generation of data management tools beyond relational databases that are currently undergoing fast development. For instance, for satellite image management and processing the Google Earth Engine is one innovative example. The prospective challenges that wildlife monitoring "Big Data" will likely pose to biologists in the next years, necessitates that data management becomes part of the training of ecologists. This will be essential to master the next generation of data management and analytical techniques, similar to those employed in bioinformatics and computational biology (Rutz and Hays, 2009).

During the past 35 years, new technologies have been developed to remotely track and studying free ranging animals, and advances in technology continue to increase opportunities for incorporating biotelemetry to study animal behaviour and ecology (Cooke et al., 2004; Ropert-Coudert and Wilson, 2005; Rutz and Hays, 2009). These advancements required many data management innovations, particularly the customization of spatial databases and the creation of specific modules that were developed during the last years and are currently being adopted by many research groups. Meanwhile, tracking technology continues to evolve and new advancements in data management in terms of methodological approaches and software tools are required to keep pace. In fact, only “integration of analytical and technical advancements within solid theoretical frameworks will allow us to tackle the intimate complexity of ecosystems, and their sensitivity to a changing planet” (Cagnacci et al., 2010). In this process, movement ecology must drive the development of these increasingly sophisticated technologies that should be prioritized according to sound hypotheses and not vice versa. This can be achieved also by gradually integrating the general concepts of advanced data management into the educational background of ecologists, as already has happened with e.g. statistics and GIS.

I aim to contribute to further research towards innovative software solutions and to support the scientific wildlife community with tools for improved and efficient data management as a key step in the scientific process. This should be grounded on an interdisciplinary approach to join scientific requirements and existing data management tools. The identification of innovative solutions generated by the “smart” integration of these two disciplines will be a valuable contribution to support rigorous science, conservation and sustainable management of natural resources.

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It is true that “no researcher is an island entire of itself; every researcher is a piece of the continent, a part of the main”. And it is particularly true in my case. This work is the result of many collaborations established in the last 8 years with dozens of colleagues from all over the world. Joining so many projects is a privilege, it teaches you a lot and you have the chance to meet and learn from other experts in different disciplines. This is a huge opportunity for a personal and professional growth. The drawback is that the list of people who deserve to be acknowledged is too long. So, I will mention here just few and will acknowledge all the others with a good beer (or a fresh orange juice) the first time I meet them again. In first place, I want to give credits to Francesca Cagnacci for half of the work presented here. This is really the result of an equal and advantageous collaboration of two persons with different background but similar attitude. Moreover, I thank Holger Dettki for his valuable technical support in the writing of this thesis, Leonardo Filesi, who accepted to be my supervisor, and all the coauthors of my publications. A special thank goes to Wibke Peters for her brilliant scientific contribution in finalising the draft of the thesis. Finally, un grazie ai miei genitori che mi hanno insegnato ad avere curiosità delle cose del mondo, a Mila, a cui spero di trasmettere la stessa passione, e a Olja. Ci aspettano ancora molte avventure.

Annex 1 - List of Papers and Book Chapters Published

PAPERS ON ISI-INDEXED JOURNALS

- Debeffe L., **Urbano F.** et al.: *A one night stand? Reproductive excursions of female roe deer as a breeding dispersal tactic*. Oecologia, 2014 [I.F. 2014: 4.538]. doi:10.1007/s00442-014-3021-8
- Eerens H., **Urbano F.** et al.: *An image time series processing software for agriculture monitoring*. Environmental Modelling and Software, 2014 [I.F. 2014: 3.476]. doi:10.1016/j.envsoft.2013.10.021
- Meroni M., **Urbano F.** et al.: *Early detection of biomass production deficit hot-spots in semi-arid environment using FAPAR time series and a probabilistic approach*. Remote Sensing of Environment, 2014 [I.F. 2014: 5.103]. doi:10.1016/j.rse.2013.11.012
- Morellet N., **Urbano F.** et al.: *Seasonality, weather, and climate affect home range size in roe deer across a wide latitudinal gradient within Europe*. Journal of Animal Ecology, 2013 [I.F. 2014: 4.937]. doi:10.1111/1365-2656.12105
- Meroni M., **Urbano F.** et al.: *A phenology-based method to derive biomass production anomalies for food security monitoring*. International Journal of Remote Sensing, 2013 [I.F. 2014: 1.117]. doi:10.1080/01431161.2014.883090
- Cagnacci F., **Urbano F.** et al.: *Partial migration in roe deer: migratory and resident tactics are end points of a behavioural gradient determined by ecological factors*, Oikos, 2011 [I.F. 2014: 3.393]. doi:10.1111/j.1600-0706.2011.19441.x
- **Urbano F.**, Cagnacci F. et al.: *Wildlife tracking data management: a new vision*. Philosophical Transactions of the Royal Society B. 365 (1550): 2177-2185, July 2010 [I.F. 2014: 6.1]. doi:10.1098/rstb.2010.0081
- Dunham K.M., **Urbano F.** et al.: *Human-wildlife conflict in Mozambique: a national perspective*. Oryx, 2010 [I.F. 2014: 2.2]. doi:10.1017/S003060530999086X
- Cagnacci F., **Urbano F.**: *Managing wildlife: a spatial information system for GPS collars data analysis and modelling*. Environmental Modelling and Software, 2008 [I.F. 2014: 4.538]. doi:10.1016/j.envsoft.2008.01.003

BOOKS

- **Urbano F.**, Cagnacci F. (eds.): *Spatial Database for GPS Wildlife Tracking Data*. Springer International Publishing Switzerland 2014. doi:10.1007/978-3-319-03743-1

CHAPTERS IN BOOKS

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